PROBING RADIATION PRESSURE INSTABILITIES IN NEUTRON STAR LMXBS

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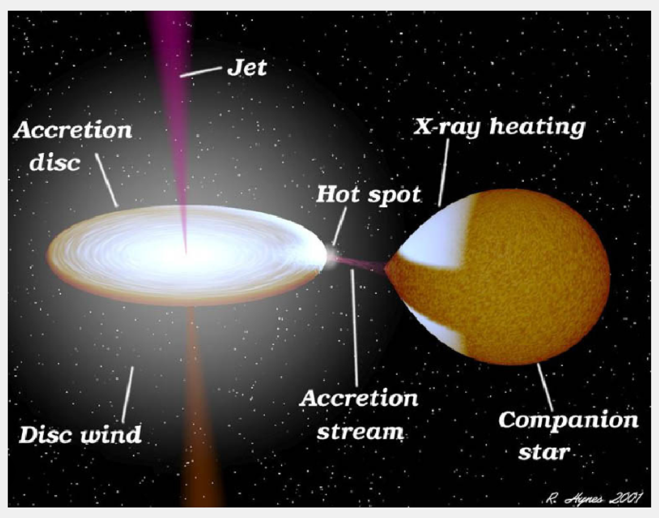
I. Accretion onto the NS

- Neutron stars (NS) in binary systems accrete matter from their companion stars, as in **Low-Mass X-ray Binaries (LMXBs),** where the companion is a low-mass star.
- Accreting star from the star forms a disc before falling onto the neutron star, releasing gravitational energy and producing high-energy radiation, primarily as X-rays.
- In the spectra of such accreting NSs, different features are observed depending upon the properties of the system such as rate of accretion and NS magnetic field.



Representation of a Low Mass Xray Binary, Source : CESAR ESA

II. Sub-Keplerian accretion disk around a NS

- To include the effect of the flux from the neutron star boundary layer, we solve the following three equations :

Energy Balance equation

$$Q_{cool} - Q_{grav,kin} - Q_{trans} = 0 \quad (1)$$

$$Q_{cool} = \frac{4\sigma_{bol}}{3c}\frac{T^4}{\rho H}, \; Q_{gravkin} = \frac{\dot{M}}{4\pi r}(\Omega_K^2 r + \Omega^2 r + \Omega r^2 \frac{d\Omega}{dr})$$

$$Q_{trans} = -\frac{\dot{M}}{4\pi r}\frac{d}{dr}(\Omega^2 r^2 - j\Omega\Omega_{NS}^K R_{NS}^2)$$

Equation for Sub-Keplerian angular velocity of the disk and radial pressure gradient

$$\frac{d\Omega}{dr} = \frac{v_r}{\nu r^2}(\Omega r^2 - j\Omega_{NS}^K R_{NS}^2) \; ; \; v_r\frac{dv_r}{dR} + \frac{dP}{dr} = (\Omega^2 - \Omega_k^2)\rho r \quad (2)$$

where j is an scaling factor, showing the ratio of sub-keplerian angular momentum.

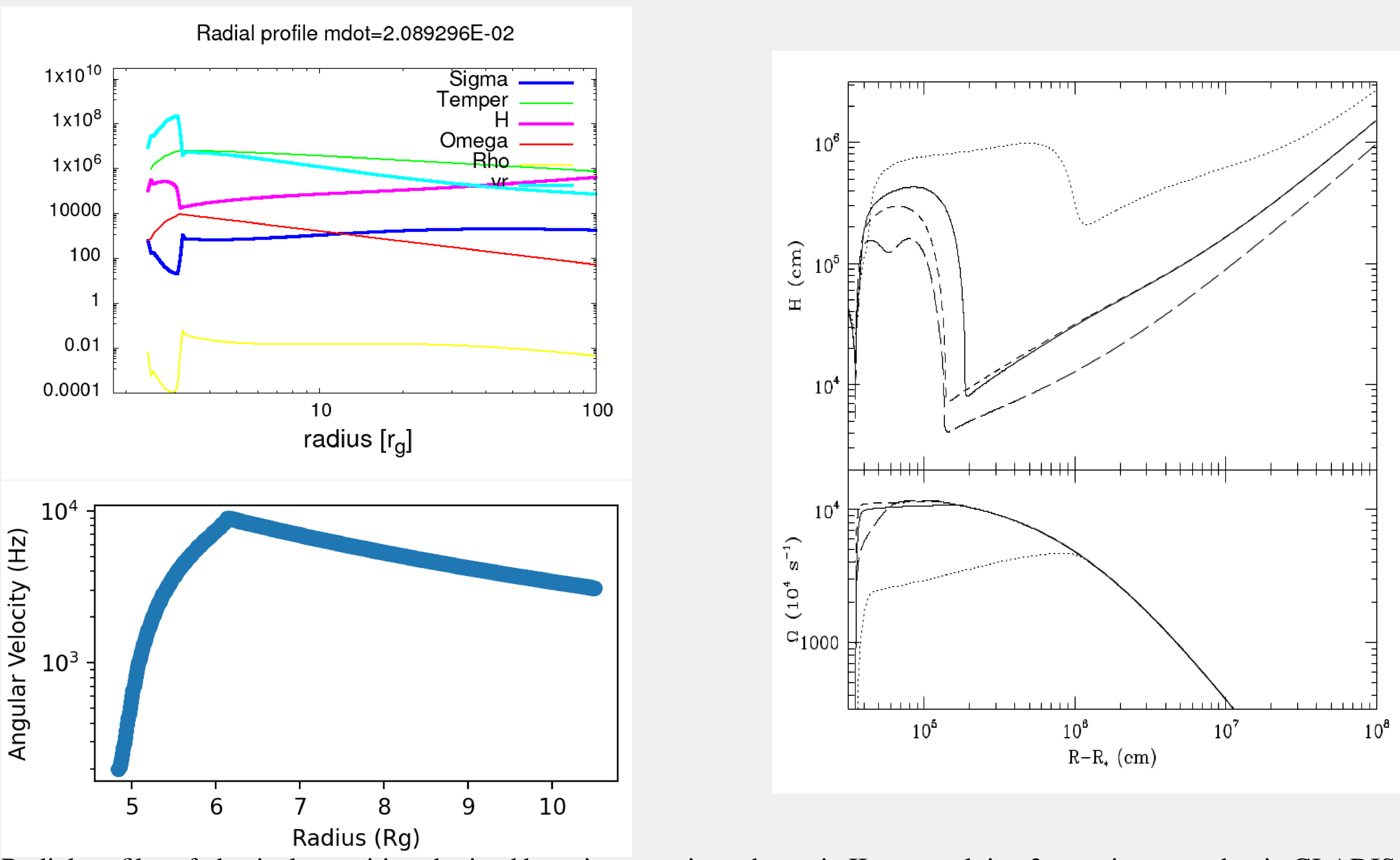
- For the non-Keplerian regime, these equations from Popham and Sunyaev (2001) are used to solve for temperature (T), angular velocity (Ω) and height (H).
- Further, we use the equation of state to obtain pressure (P) and vertically averaged hydrostatic equilibrium density (ρ)

$$P = \frac{4\sigma_{bol}}{3c}T^4 + \frac{K_b}{m_H}\rho T \; ; \; \frac{P}{\rho} = C\Omega_k^2 H^2 \quad (3)$$

where C is a coefficient used in vertically averaging of the equilibrium relation.

III. Time-independent radial profiles for accretion disk

For typical NS parameters, $M_{NS} = 1.4 M_\odot$, $R_{NS} = 10^6$ cm , $\Omega_{NS} = 100$, j = 1.06.



Radial profiles of physical quantities obtained by using equations shown in II, top : solving 3 equations together in GLADIS, bottom : solving algebraic equations separately than radial differential equations, Right : Expected radial profile around boundary layer radius from Popham and Sunyaev (2001).

References

References

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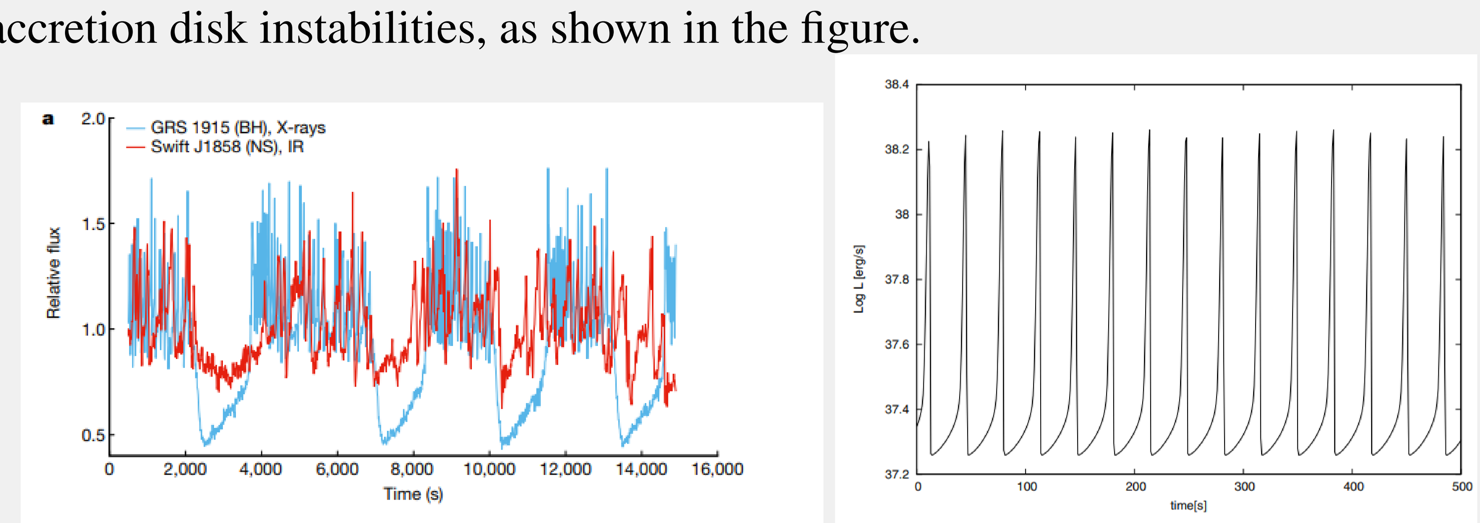
IV. Instabilities in NS and BH accretion disks

- Radiation pressure instabilities (RPIs) are thermoviscous instabilities from inner portions of accretion disks, causing short-term variations in the X-ray emission, on timescales of seconds.
- Janiuk et al. (2002) model explained these variabilities due to RPIs in black hole X-ray binaries, such as GRS 1915-105.
- Recently, Vincentelli et al. (2023) demonstrated that neutron stars exhibit similar accretion disk instabilities, as shown in the figure.



Left : Short-term variabilities in SWIFT-J1858.6-0814 , Source : Vincentelli et al. (2023)

Right : Instabilities obtained by Janiuk et al. (2015) using the GLADIS code to model a black hole accretion disk instability for the microquasar IGR J17091-3624

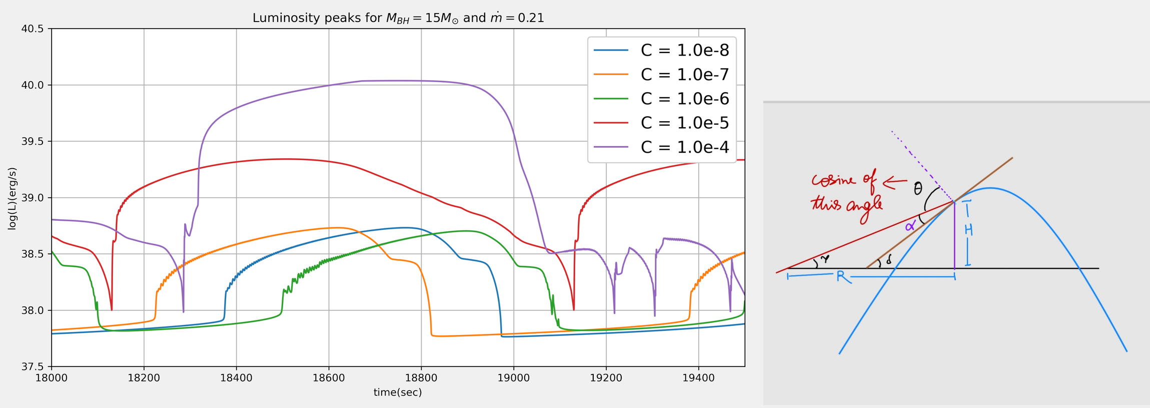
V. Effect of irradiation from the central region

- The effect of irradiation from the compact corona in central region around the NS/BH changes the temperature profile of the disc, affecting the onset and the behaviour of the disc instabilities. We include radiative cooling and effective irradiation onto the disk from Dubus et al. (1999),

$$T_c^4 = \frac{3}{8}\tau_{tot}T_{eff}^4 + T_{irr}^4 \; ; \; T_{irr}^4 = C\frac{\dot{M}c^2}{4\pi R^2} \quad (4)$$

- The factor C includes the constants and geometrical factor $Cos(\theta)$. η denotes the efficiency of accretion energy getting comverted into X-rays and $1 - \epsilon$ shows the fraction of X-ray absorbed in the optically thick layers of the disk.
- The geometrical factor $Cos(\theta)$ takes the effect of shape of the pulse in accretion disk in the irradiation flux.

$$C = \eta(1-\epsilon)Cos(\theta) \; ; \; Cos(\theta) = \frac{1 + \frac{H_{irr}}{R}\frac{d \ln H_{irr}}{d \ln R}}{\sqrt{(1 + (\frac{H_{irr}}{R})^2)(1 + (\frac{d \ln H_{irr}}{d \ln R})^2)}} \quad (5)$$



Luminosity peaks occurring at different times in the unstable evolution of an accretion disk around a black hole for different C values, Right : Geometrical picture of irradiation flux component on the disk pulse

Summary

- We computed the stationary structure of sub-Keplerian accretion disks where $\Omega(r) < \Omega_K(r)$, This boundary layer(BL) portion of the disk turns out to be within $(1.30, 1.50)R_{NS}$, where R_{NS} is the radius of the NS. We can assume $\Omega(r) \sim \Omega_K(r)$ at larger radii, outside BL.
- The BL shows different structure than the usual Shakura-Sunayev's disk. It results from the balance between radiative cooling and the energy released by the gas in the process of accretion - gravitational and kinetic energy is redistributed inside BL down the local gradient of Ω.
- Boundary layer thickness depends upon the NS parameters such as Ω_{NS} and j. Values of dimensionless parameter "j" are allowed between (0.66, 1.24) to produce stable solutions for the stationary case.
- We compute the effect of irradiation only from the point source above the compact object i.e. for BHs. We probe several values of modified Dubus' C coefficient in the range 10^{-3} to 10^{-8}, following the time evolution of the Keplerian disk under dominant P_{rad} instability.
- We observe broad instability peaks with irradiation, characteristically different from the sharp narrow peaks obtained without irradiation, shown in Panel IV. Further, the duration of these peaks lie in the range of 600-1200 secs, slightly less than the duration of longer peaks ($\sim$ 1000-2000 secs) observed by Vincentelli et al. (2023), shown in Panel IV.

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